International Journal of Applied Aviation Studies, Volume 6, Number 1

Retention of Aeronautical Knowledge

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Abstract

Pilots' retention of aeronautical knowledge learned during private pilot training was studied in four experiments. In the first experiment, ten questions from the FAA private pilot airplane knowledge test were administered to sixty pilots, yielding an average score of 74.8%. Test scores were compared against seven characteristics of the pilots tested: certificates and ratings held, current role in aviation (pilot, CFI, or applicant for additional certificate/rating), total flight time, recent flight experience, reading habits, months passed since last evaluation, and months remaining until next evaluation. These factors explain some of the overall variability in test scores. Three follow-up experiments explored hypotheses about how retention might be affected by pilots' working environment: (1) pilots' knowledge becomes tuned to familiar aircraft charts; (2) difficult-to-remember regulations prompt pilots to substitute simpler rules that still allow them to operate legally; and (3) pilots' geographical region reinforces knowledge about local weather patterns, while knowledge of different weather patterns falls to disuse. The results well support two of these hypotheses but also further demonstrate that there are no simple-to-measure determinants of what aeronautical knowledge will be remembered and forgotten. The experience of everyday flying or teaching, together with recent flight experience and flight review requirements, does not appear to eliminate the need for ongoing study or rehearsal of aeronautical knowledge.

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Introduction

Learning to operate an aircraft requires the pilot to master a formidable amount of aeronautical knowledge. Knowledge about weather, regulations, aerodynamics, airspace, navigation, and aircraft systems and performance serves as the basis of pilot decision-making and actions. Mastering this aeronautical knowledge is known to be a laborious task, one that requires many hours of study (Flouris, 2001; Casner, Jones, Puentes, & Irani, 2003). In addition, after the pilot has initially learned this compendium of aeronautical knowledge, comes a second challenge: the challenge of remembering it.

It is well known that human memory is far from perfect, and it is natural that pilots will remember some of the things they have learned while they struggle to remember others. Hypotheses about what aeronautical knowledge is remembered and what is forgotten are easy to make. Memory research suggests that our ability to remember the things we have learned can best be summarized by a familiar adage: "Use it or lose it." Specifically, the ability to retrieve any particular item from memory seems to be largely determined by how many times that knowledge has been used in the past, and how recently the knowledge has been used (Anderson, 1976). Therefore, it seems that everyday knowledge, such as aircraft performance and regulations that apply to routine flight, should be well retained; while less frequently used knowledge, such as emergency procedures and biannual inspection requirements, might fall to disuse. Of course, if our aim is to provide pilots with specific helpful advice, or perhaps to influence policy, we will need to be more systematic about making and validating our predictions.

One approach might be to attempt to catalogue which aeronautical facts and concepts pilots must recall and use throughout the course of their everyday activities, and to make predictions based on these usage profiles (Anderson, 1990; Newell & Rosenbloom, 1981). Unfortunately, for a domain as wide and rich as aviation, this process would seem to be both prone to error and laden with assumptions.

We adopt a more practical approach here by working the problem in reverse. We begin by capturing some of what pilots have remembered and forgotten. We then gather facts about the pilots, their past and present aviation experiences, the environment in which they operate, and some characteristics of the aeronautical knowledge itself. Finally, we attempt to link these characteristics of person, place, and thing to the observed patterns of pilot remembering and forgetting. Such an analysis should not only help identify knowledge areas that are prone to disuse and forgetting, but also help to reveal why.

In Experiment 1, we asked pilots to answer ten questions drawn from the FAA private pilot knowledge test to pilots and to provide us with details about themselves and their experiences. The data were analyzed to answer questions such as:

1. Does holding more certificates and ratings make pilots more likely to remember what they have learned?

2. Does more total or recent flight time lead to better retention?
3. Do flight instructors remember more after having taught the same material over and over again?
4. Do pilots remember more just before or after a flight review or practical test?

In Experiments 2 through 4, different pilots were asked to answer further questions to examine the influence of the kind of knowledge that pilots must remember, the materials that pilots use, and the characteristics of the places in which pilots fly. These data allow us to answer the following questions.
1. Is some aeronautical knowledge harder to remember than other knowedge?
2. Do the particular aircraft that pilots fly reinforce certain types of knowledge?
3. Do pilots better remember aeronautical knowledge that applies to their own familiar geographical regions?

We conclude by making some practical recommendations for how to improve the state of affairs for pilot knowledge retention, and by reviewing some important limitations of our study.

Experiment 1

In our first experiment, we administered ten questions drawn from the FAA private pilot knowledge exam to sixty pilots and asked them to provide us with details about seven aspects of their past and present aviation experience:
1. Certificates and ratings held;
2. Current role in aviation (active flight instructor, applicant for additional FAA certificate or rating, neither instructor nor applicant);
3. Total flight time;
4. Recent flight time (last 6 months, last 3 months);
5. Months since last flight review;
6. Months until next practical test (if applicant for additional certificate or rating);
7. Reading habits.

Apparatus

A paper and pencil, multiple-choice test was used for data collection. Each test contained the same ten questions randomly selected from the FAA private pilot item bank of questions. Questions that required extensive calculations (e.g., cross-country flight planning) were excluded, as were multiple questions drawn from the same topic area. The test was accompanied by a questionnaire that asked participants about the seven aspects of their past and recent aviation experience listed above.

Participants

Sixty pilots recruited from California Bay Area airports participated in the study. To insure a more uniform distribution of pilots across our seven aspects of pilot experience variables, we recruited pilots in equal numbers from the three categories of the current role in aviation variable. Twenty participants were active certified flight instructors (CFI group). Twenty participants held at least a private pilot certificate and were actively working toward an additional FAA pilot certificate or rating (Applicant group). Twenty participants were active pilots, holding at least a private pilot certificate, but were neither CFIs nor Applicants (Pilot group). Pilots were recruited for each category on a volunteer, first-come-first-served basis until each category was filled. Pilots received a NASA Aviation t-shirt as compensation for participating in the study.

Procedure

The experimental tests were completed by participants at times of their choosing. There was no time limit for completing the test. All participants were informed that their responses would remain anonymous.

Results and Discussion

Figure 1 shows a plot of the individual test scores for all pilots tested.

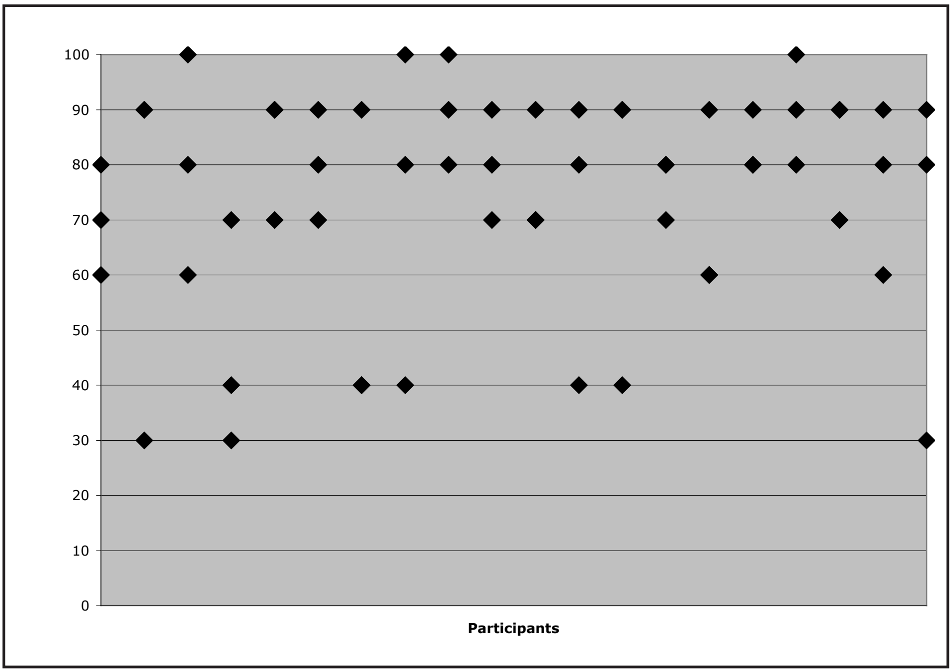


Figure 1. Test scores for all pilots tested.

Overall Test Performance. The results indicated a generally unimpressive overall performance. The average score for all sixty pilots was 74.8% with a standard deviation of 19.3%. Only 62% of all participants obtained a score higher than what is considered passing on the FAA private pilot knowledge test (70%). 15% of all participants obtained a score of 70%. 23% scored below 70%. Although a formal comparison was inappropriate due to the small sample size and limited variety of questions used here, it is interesting to note that only 38% scored higher than the national average score for the FAA private pilot airplane knowledge test (85%) (FAA, 2003).

It is important to reiterate that every participant in the study held at least an FAA private pilot certificate. That is, at some point in the past, every participant had achieved a passing score on the private pilot knowledge test from which the experimental test questions were drawn.

The data clearly showed that significant forgetting of the material tested by the FAA questions had taken place.

Certificates and Ratings Held. The scores for all pilots were segregated in four groups based on the certificates and ratings held by each pilot. The four groups and their mean scores were as follows: Private Pilot = 70.5% (21.1%); Private Pilot w/Instrument Rating = 77.8% (17.9%); Commercial Pilot = 72.2% (20.5%); and Certified Flight Instructor = 79.1% (17.6%). No significant differences were found among any of the four groups. Although there is considerable overlap in the aeronautical knowledge required for each successive pilot certificate, requiring pilots to study similar material repeatedly as they progress, the data did not indicate an improvement in retention due to training experience.

Current Role. The purpose of our three experimental groups was to measure the effect of the role that each pilot currently assumes on retention of aeronautical knowledge. It is important to note that this variable represents a notion different from that of certificates and ratings held by each pilot participant. The current role variable describes what each pilot is currently doing with the certificates and ratings that they hold. A participant in the Pilot group may have been a member of the Applicant group earlier that week before passing an Airline Transport Pilot practical test. Similarly, a member of the Applicant group may have been a member of the Pilot group a week earlier simply by deciding to pursue a Flight Instructor certificate. Thus, the three groups describe the status of pilot participants on the day and time that the test was administered.

The mean scores and standard deviations for the CFI, Applicant, and Pilot groups are shown in Table 1:

Table 1
Mean test scores and standard deviations for the three groups.

	CFI Group	**Applicant Group**	**Pilot Group**
Mean	79.0	76.0	69.5
Standard Deviation	18.0	17.0	22.1

A comparison of the means between the three groups revealed a marginally significant difference between the CFI and Pilot groups (df=18, t=1.49, $p < 0.09$). The large variability in scores among all three groups blurred the distinction between the means for all three groups. This result generally supports the idea that flight instructors rehearse their knowledge more often than other pilots do, and that leads to better retention. This result puts an interesting twist on the earlier finding about certificates and ratings held. Knowledge retention seemed to be affected not by the holding of certificates and ratings, but to some extent, what pilots are currently doing with those certificates and ratings.

Total and Recent Flight and Teaching Experience. The total and recent flight experience for all pilots tested is shown in Table 2, along with correlation coefficients comparing flight experience and scores on the experimental test.

Table 2
Correlations between test scores and total and recent flight experience.

	Total Flight Time		Past 6 Months		Past 3 Months	
	Hours	r	Hours	r	Hours	r
Pilot Group	382	.05	35	.21	13	.31
Applicant Group	272	.37	57	.14	32	-.21
CFI Group	1294	.04	178	**.47**	94	**.52**
All Three Groups	649	.11	90	**.34**	46	**.31**

There was little observed correlation between test scores and total flight experience. The three groups combined showed significant correlations between test scores and flight experience during the past six months (df=58, t=2.75, $p < .01$) and the past three months (df=58, t=2.48, $p < .01$). Most of this correlation is accounted for by the CFI group: past six months (df=18, t=2.26, $p < .05$), and past three months (df=18, t=2.58, $p < .01$).

Upcoming and Past Evaluations. There are generally two types of formal evaluations for the population of U.S. pilots: practical tests and flight reviews. The pilots in the Applicant group, by definition, were preparing for upcoming practical tests. All sixty of our pilot participants are subject to a flight review every 24 calendar months.

A significant negative correlation found was between test scores for the Applicant group and number of months remaining until the applicant's upcoming practical test (r=-0.68, df=18, t=3.93, $p < .005$). The closer each applicant was to their future practical test, the higher were their scores.

A similar correlation was found between test scores for the Pilot group and number of months since each pilot's last flight review ($r=-.44$, $df=18$, $t=1.96$, $p < .05$). Recently completed flight reviews were associated with higher scores. This result suggested that the flight review requirement only modestly serves to maintain pilot mastery of aeronautical knowledge.

Reading Habits. All pilots were asked to provide a Likert-type response to the question: "How often do you read magazines or books about flight training topics?" Interestingly, there were no differences in the reported reading frequency between the Pilot, Applicant, and CFI groups. Correlation coefficients for reading frequency and experimental test scores are shown in Table 3.

Table 3
Correlations between test scores and reported reading frequency

	r
Pilot Group	-.02
Applicant Group	.53 **
CFI Group	.05
All Three Groups	.14

A significant correlation was observed for the Applicant group ($df=18$, $t=2.65$, $p < .01$). The more time that these pilots reported that they spent reading, the better they did on the experimental test.

Summary

Overall, the seven aspects of pilot experience account for only modest portions of the variability in scores we observed. The data clearly showed that there is much more to the story about knowledge retention than certificates and ratings, flight time, and upcoming flight reviews and check rides. Pursuing these goals alone does not ensure that pilots will remember what they have learned.

Performance on individual questions

We then turned to a consideration of the ten test questions that pilots were asked to answer. This analysis allowed us to further explore links between which knowledge areas are used more frequently and which are retained and forgotten.

A breakdown of scores on each of the ten questions is shown in Figure 2. The results were further broken down by the current role for each pilot participant (i.e., CFI, Applicant, or Pilot).

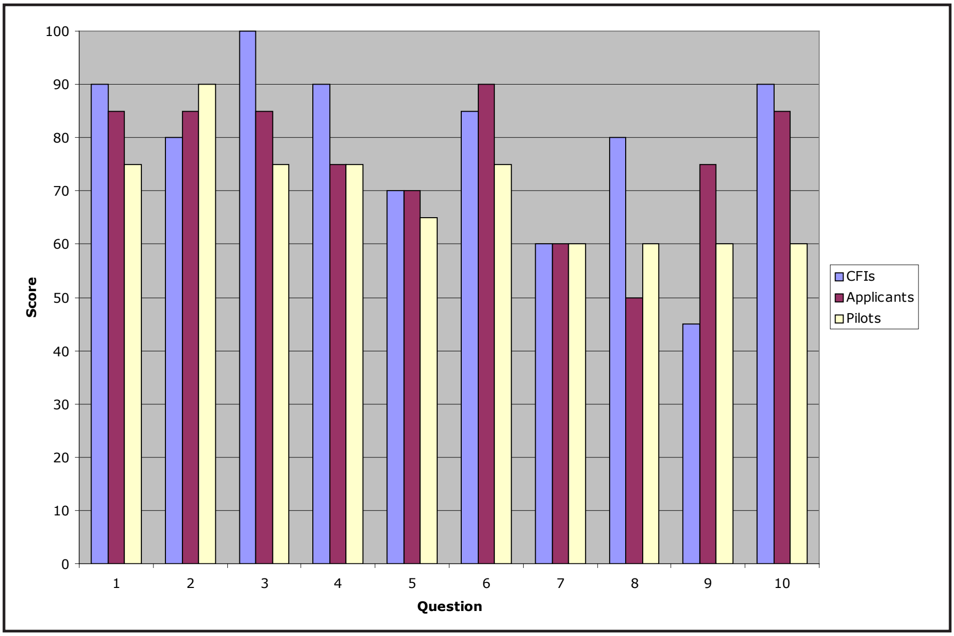


Figure 2. Scores for individual questions broken down by current role factor.

A correlation matrix comparing scores on individual questions to the remaining six factors of pilot experience is shown in Table 4. Significant correlations are shown in bold.

Table 4
Correlation coefficients comparing scores on individual questions to pilot experience.

	Question									
	1 Mag. Comp	2 W&B	3 Ceil-ing	4 Light Gun	5 Dens. Alt.	6 ELT	7 Night Flight	8 VOR	9 Alt. & Temp	10 Class G
Total Flight Time										
CFIs	-.07	.09	-	.13	.19	-.1	-.21	.33	-.29	.31
Applicants	.08	.05	.14	**-.44**	.2	-.7	.28	.27	.16	.11
Pilots	.03	.18	.3	.18	.17	**-.4**	-.16	-.2	-.02	.17
Combined	.06	.03	.2	-.01	.17	-.2	-.02	**.27**	.17	**.24**
Last 6 Months										
CFIs	.31	.16	-	.31	0.0	.2	.24	**.46**	.17	.33
Applicants	.29	-.15	.27	**-.56**	.15	0.0	.34	.17	.06	0.0
Pilots	.2	.05	.24	.24	.17	.2	.23	.23	**-.39**	-.12
Combined	**.25**	.02	.2	.17	.05	.2	.17	**.34**	-.06	**.22**
Last 3 Months										

CFIs	**.4**	.17	-	.37	-.05	.3	.2	**.58**	.27	.18
Applicants	.24	0.0	-.09	**-.61**	-.11	0.0	.13	-.01	-.22	.11
Pilots	.17	-.15	.25	.2	.22	.1	.24	.31	-.31	**.39**
Combined	**.28**	.01	.19	.13	0.0	.2	.12	**.34**	-.04	**.25**
Reading Frequency										
CFIs	-.35	-.2	-	-.13	-.04	**.6**	.08	0.0	.16	-.02
Applicants	.12	-.22	**.81**	.14	.37	-.2	.3	.2	.33	.13
Pilots	.05	.26	.25	.12	.2	-.3	-.19	-.25	-.36	.16
Combined	-.03	-.05	**.35**	.05	.17	0	.04	-.03	.01	.11
Next Practical										
Applicants	-.1	.17	**-.7**	-.21	**-.5**	.1	**-.57**	-.2	**-.46**	-.1
Last Flight Review										
Pilots	.21	.11	-.33	**-.5**	-.36	**-.4**	-.24	-.2	.07	-.2
Certificates/Ratings										
Applicants	-.02	-.02	-.02	-.07	-.15	.2	.37	-.1	-.25	.15
Pilots	.26	.33	.26	.11	-.1	0.0	0.0	0.0	.13	-.13
Combined	.12	.14	.12	.02	-.13	0	.2	0	-.07	-.03

The analysis of the ten individual questions below makes frequent reference to the data presented in Figure 2 and Table 4.

Question 1. In the Northern Hemisphere, a magnetic compass will normally indicate initially a turn toward the east if:
A—an aircraft is decelerated while on a south heading.
B—an aircraft is accelerated while on a north heading.
C—a left turn is entered from a north heading.

This question asked about a compass turning error that is likely observed more in a training environment, and only occasionally during training, since the magnetic compass is not considered a primary flight instrument. Indeed, the significant correlations between scores on this question and flight experience during the past three months were mainly due to CFIs and applicants. The Pilot group also performed admirably on this question, perhaps because pilots are taught a memory aid to help them to remember this turning error (ANDS – Accelerate North, Decelerate South) (FAA, 1999; Jeppesen Sanderson, 1999; Kershner, 2001; Gardner, 2002). The effectiveness of mnemonics like this one has been widely demonstrated (Baddeley, 1998; Yates, 1966).

Question 2. (Refer to Figure 3) Determine if the airplane weight and balance is within limits.
Front seat occupants……………………………..415 lb
Rear seat occupants………………………………110lb

Fuel, main tanks……………………………….44 gal
Fuel, aux. Tanks……………………………….19 gal
Baggage…………………………………………32 lb

A—19 pounds overweight, CG within limits.

B—19 pounds overweight, CG out of limits forward.

C—Weight within limits, CG out of limits.

MOMENT LIMITS vs WEIGHT (Continued)

Weight	Minimum Moment / 100	Maximum Moment / 100
2100	1617	1800
2110	1625	1808
2120	1632	1817
2130	1640	1825
2140	1648	1834
2150	1656	1843
2160	1663	1851
2170	1671	1860
2180	1679	1868
2190	1686	1877
2200	1694	1885
2210	1702	1894
2220	1709	1903
2230	1717	1911
2240	1725	1920
2250	1733	1928
2260	1740	1937
2270	1748	1945
2280	1756	1954
2290	1763	1963
2300	1771	1971
2310	1779	1980
2320	1786	1988
2330	1794	1997
2340	1802	2005
2350	1810	2014
2360	1817	2023
2370	1825	2031
2380	1833	2040
2390	1840	2048
2400	1848	2057
2410	1856	2065
2420	1863	2074
2430	1871	2083
2440	1879	2091
2450	1887	2100
2460	1894	2108
2470	1902	2117
2480	1911	2125
2490	1921	2134
2500	1932	2143
2510	1942	2151
2520	1953	2160
2530	1963	2168
2540	1974	2176
2550	1984	2184
2560	1995	2192
2570	2005	2200
2580	2016	2208
2590	2026	2216

Weight	Minimum Moment / 100	Maximum Moment / 100
2600	2037	2224
2610	2048	2232
2620	2058	2239
2630	2069	2247
2640	2080	2255
2650	2090	2263
2660	2101	2271
2670	2112	2279
2680	2123	2287
2690	2133	2295
2700	2144	2303
2710	2155	2311
2720	2166	2319
2730	2177	2326
2740	2188	2334
2750	2199	2342
2760	2210	2350
2770	2221	2358
2780	2232	2366
2790	2243	2374
2800	2254	2381
2810	2265	2389
2820	2276	2397
2830	2287	2405
2840	2298	2413
2850	2309	2421
2860	2320	2428
2870	2332	2436
2880	2343	2444
2890	2354	2452
2900	2365	2460
2910	2377	2468
2920	2388	2475
2930	2399	2483
2940	2411	2491
2950	2422	2499

USEFUL LOAD WEIGHTS AND MOMENTS

OCCUPANTS

FRONT SEATS ARM 85		REAR SEATS ARM 121	
Weight	Moment / 100	Weight	Moment / 100
120	102	120	145
130	110	130	157
140	119	140	169
150	128	150	182
160	136	160	194
170	144	170	206
180	153	180	218
190	162	190	230
200	170	200	242

BAGGAGE OR 5TH SEAT OCCUPANT ARM 140

Weight	Moment / 100
10	14
20	28
30	42
40	56
50	70
60	84
70	98
80	112
90	126
100	140
110	154
120	168
130	182
140	196
150	210
160	224
170	238
180	252
190	266
200	280
210	294
220	308
230	322
240	336
250	350
260	364
270	378

USABLE FUEL

MAIN WING TANKS ARM 75

Gallons	Weight	Moment / 100
5	30	22
10	60	45
15	90	68
20	120	90
25	150	112
30	180	135
35	210	158
40	240	180
44	264	198

AUXILIARY WING TANKS ARM 94

Gallons	Weight	Moment / 100
5	30	28
10	60	56
15	90	85
19	114	107

***OIL**

Quarts	Weight	Moment / 100
10	19	5

*Included in basic Empty Weight

Empty Weight ~ 2015

MOM / 100 ~ 1554

MOMENT LIMITS vs WEIGHT

Moment limits are based on the following weight and center of gravity limit data (landing gear down).

WEIGHT CONDITION	FORWARD CG LIMIT	AFT CG LIMIT
2950 lb (takeoff or landing)	82.1	84.7
2525 lb	77.5	85.7
2475 lb or less	77.0	85.7

Figure 3. Weight and balance charts for Question 2

The correct answer to this question is that the aircraft is not approved to fly as it is currently loaded. The Pilot group performed best while only eighty percent of the CFI group answered the question correctly. This might be attributed to flight instructors not working many weight and balance problems. Instructors might leave this type of problem solving to students to learn on their own, or in a ground school. In addition, training flights seldom exceed the weight and balance limitations and instructors might simply skip the calculations. Pilots flying outside of a training environment may be more often confronted with novel aircraft loading situations. There were no significant correlations between scores on this question and any of the seven factors we considered.

Another possible explanation for less than perfect performance is a well-known outcome of the learning process (Anderson, 2000). After initially learning the concepts needed to solve weight and balance problems, pilots' skills may become tuned to the particular charts they currently use. Their ability to solve weight and balance problems with unfamiliar charts may be less, until they have had a chance to practice a few times with them. Indeed, every insurance company requires every pilot, regardless of experience level, to complete a checkout for each new make and model of aircraft they intend to fly.

Question 3. For aviation purposes, ceiling is defined as the height above the Earth's surface of the

A – lowest reported obscuration and the highest layer of clouds reported as overcast.
B – lowest broken or overcast layer or vertical visibility into an obscuration.
C – lowest layer of clouds reported as scattered, broken, or thin.

The three groups of pilots collectively recorded the highest average score on this question. Information about cloud layers and obscurations is given in METARs. The term ceiling is used when describing cloud layers and obscurations in ATIS, AWOS, and ASOS reports. Hence, it is reasonable to assume that all pilots get regular practice with dealing with the definition of a ceiling. There was a strong correlation between scores on this question and reading frequency among the Applicant group.

Question 4. While on final approach for landing, an alternating green and red light followed by a flashing red light is received from the control tower. Under these circumstances, the pilot should

A—discontinue the approach, fly the same traffic pattern and approach again, and land.
B—exercise extreme caution and abandon the approach, realizing the airport is unsafe for landing.
C—abandon the approach, circle the airport to the right, and expect a flashing white light when the airport is safe for landing.

Question 4 is a classic example of an emergency procedure that is seldom rehearsed outside of flight training environments. However, light gun signals, to some extent, make use of universal conventions, namely that green generally signals that it is okay to proceed, while red signals stop. These conventions are well known to aid memory (Yates, 1966). Interestingly, there were strong negative correlations between scores for this question and total and recent flight experience for the Applicant group.

Question 5. (Refer to Figure 4) Determine the density altitude for these conditions:

Altimeter setting …………………………………….. 30.35
Runway temperature ………………………….…… + 25 F
Airport elevation …………………...…….. 3,894 ft MSL

A—2,000 feet MSL.
B—2,900 feet MSL.
C—3,500 feet MSL.

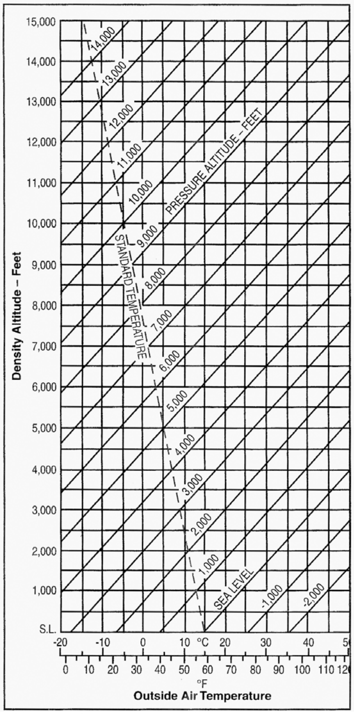
Question 5 is a simple density altitude problem. Only 70 percent of participants in the CFI and Applicant groups, and 65 percent in the Pilot group answered the question correctly. This is particularly worrisome given that density altitude calculation is an important, often critical, skill. One possible explanation for this result is that all participants in the study were drawn from the coastal region of California where high density altitude is seldom encountered. Another possible explanation is that many aircraft performance charts integrate density altitude information into the chart, eliminating the need to calculate density altitude explicitly. Hence, that technique may have fallen to disuse. There was a strong correlation between scores on this question and time remaining until an upcoming practical test for pilots in the Applicant group: the closer they got to the practical test, the better they did on the density altitude question.

Question 6. When are non-rechargeable batteries of an emergency locator transmitter (ELT) required to be replaced?

A—Every 24 months.
B—When 50 percent of their useful life expires.
C—At the time of each 100-hour or annual inspection.

The Applicant group recorded the best performance on this question, and good performance was strongly associated with greater reading frequency. A possible explanation for the moderate performance among the CFI and Pilot groups might be that many flying schools/clubs have a maintenance board showing due dates for required inspections. Or that club managers ensure that airplanes meet inspection requirements. This knowledge is also supported by a mnemonic. ELT batteries must be replaced every “12-1-1/2”: every 12 calendar months, after 1 hour of continuous use, or after 1/2 of their useful life has expired.

DENSITY ALTITUDE CHART



Altimeter Setting (" Hg)	Pressure Altitude Conversion Factor
28.0	1,824
28.1	1,727
28.2	1,630
28.3	1,533
28.4	1,436
28.5	1,340
28.6	1,244
28.7	1,148
28.8	1,053
28.9	957
29.0	863
29.1	768
29.2	673
29.3	579
29.4	485
29.5	392
29.6	298
29.7	205
29.8	112
29.9	20
29.92	0
30.0	-73
30.1	-165
30.2	-257
30.3	-348
30.4	-440
30.5	-531
30.6	-622
30.7	-712
30.8	-803
30.9	-893
31.0	-983

Figure 4. Density altitude chart for Question 5.

Question 7. If recency of experience requirements for night flight are not met and official sunset is 1830, the latest time passengers may be carried is

A – 1929.
B – 1829.
C – 1859.

Question 7 asked pilots to determine how late in the day they can legally fly with passengers when they are not "night current." It is reasonable to assume that decisions about night currency come up frequently in everyday practice. Surprisingly, forty percent of pilots in all three groups answered this question incorrectly. This regulation is another example of a fact that must be memorized, in this case, without the benefit of a memory aid or mnemonic. A further explanation for the poor performance is that pilots may use their own informal rules for estimating the beginning of official night. Being on the ground well before darkness would allow pilots to easily abide by the regulation without remembering its specifics. The only encouraging result was pilots in the Applicant group did better on this question as their upcoming practical test drew near.

Question 8. (Refer to Figure 5) The VOR receiver has the indications shown. What is the aircraft's position relative to the station?

A – North.
B – East.
C – South.

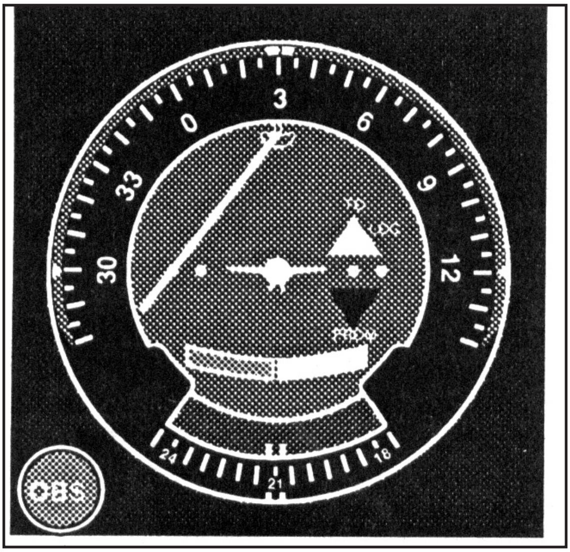


Figure 5. VOR illustration for Question 8

Question 8 asked pilots to determine their position with respect to a VOR from a single VOR indication. CFIs were the only pilots to record an even acceptable performance on this question, and this success was significantly correlated with recent flight experience. Surprisingly, only 50% of the Applicant group answered this question correctly. The most common additional rating sought by applicants is the instrument rating. VOR interpretation, of course, is a fundamental instrument skill. One explanation is that the question asks pilots to interpret a CDI indication in a way that is different from how a VOR is typically used. When determining one's position with respect to a VOR, most pilots turn the OBS knob until the needle is centered with a FROM indication, and note that they are positioned along the indicated radial. At some point, they may have learned the technique required by the question but that technique has fallen to disuse. Another possible explanation for the Pilot group is that VOR skills may be used less as the popularity of GPS navigation increases.

Question 9. How do variations in temperature affect the altimeter?

A—Pressure levels are raised on warm days and the indicated altitude is l ower than true altitude.

B—Higher temperatures expand the pressure levels and the indicated altitude is higher than true altitude.
C—Lower temperatures lower the pressure levels and the indicated altitude is lower than true altitude.

Question 9 asked pilots to apply an informal rule about changing pressure and temperature: “From high to low, look out below.” Average scores for the CFI and Pilot groups were surprisingly low for this question: 45% and 60%, respectively. One explanation for the poor scores is that there is no one accepted procedure for dealing with the effect of cold temperatures on indicated altitude. Pilots might decide to climb a few hundred feet above their planned or assigned altitude, but would have to do so at their own risk. In the absence of specific guidance, pilot may choose to disregard temperature effects. The Applicant group performed acceptably well on this question and their success was significantly correlated with time to upcoming practical test.

Question 10. What minimum visibility and clearance from clouds are required for VFR operations in Class G airspace at 700 feet AGL or below during daylight hours
A – 1 mile visibility and clear of clouds.
B – 1 mile visibility, 500 feet below, 1,000 feet above, and 2,000 feet horizontal.
C – 3 miles visibility and clear of clouds.

Question 10 asked pilots to recall a fact about VFR weather minimums in Class G airspace. The CFI and Applicant groups scored admirably well (90% and 85%, respectively). The Pilot group performed poorly (60%) and their limited successes seemed to be associated with higher flight times within the past three months. Low scores in the Pilot group may reflect the absence of an easy-to-remember memory aid for Class G minimums, or be an example of how experienced pilots often simplify difficult knowledge. The weather minimums for Question 10 are the most liberal of any type of airspace (1 SM, and clear of clouds). Pilots may choose not to rehearse this knowledge, adopting a more conservative weather minimum that allows them to abide by the regulation. It is likely a rare occasion when a pilot takes off in 1 SM and clear with the intention of remaining within 700 feet AGL. A more typical scenario is to climb to at least the traffic pattern altitude, or depart the traffic pattern, enter Class E airspace, and abide by more conservative and easy to remember weather minimums.

Summary

The analysis of individual questions casts considerable doubt on simple hypotheses about what kinds of knowledge are used and remembered and what kinds are not. The analysis proposed several more subtle factors that might help explain what is remembered and what is forgotten.

Mnemonics

Several of the questions appearing on the knowledge tested required pilots to recall facts. Some of these facts (Questions 1 and 6) were supported by popular memory aids or mnemonics that appear routinely in the textbooks used by private pilot students, while others were not (Questions 7 and 10). A comparison of scores between these two groupings of questions yielded a significant difference ($df=5$, $t=2.19$, $p < 0.05$), supporting the already widely recognized usefulness of mnemonics.

Specialization

A well-known outcome of the learning process suggested by the weight and balance and density altitude questions (Questions 2 and 5) was that as people acquire skill, their knowledge and methods tend to become finely tuned to the particular procedures and materials they use, while more general knowledge and skill becomes less available (Greeno, 1974; Logan, 1988). Pilots' ability to work problems such as weight and balance and density altitude may be highest when using familiar charts, but less when using different charts.

Simplification

A striking characteristic of many aviation regulations is that they contain intricate and sometimes similar details. The weather minimums for Class G airspace, tested by Question 10, require the pilot to remember minimum visibilities and cloud clearances for five different cases. The rules for carrying passengers at night, tested by Question 7, contain details that are similar but slightly different from related rules that govern the use of aircraft lights and the logging of night flight. The potential for memory decay and interference (Anderson, 2000) is widely recognized. A well-known outcome of the learning process is that, as people acquire expertise in a domain, they seek shortcuts and simplifications for difficult problems (Blessing & Anderson, 1996; Koedinger & Anderson, 1990; Casner & Larkin, 1989). Pilots might simplify these rules by adopting a higher standard that allows them to remain legal in all cases, and excuses them from having to remember the details.

Characteristics of the Pilot's Geographical Environment

The analysis of questions 5 and 9 proposed the idea that different geographical areas may afford opportunities to rehearse and retain, or disuse and forget, different aeronautical knowledge. Our sample of pilots was drawn from the coastal region of California. In their home environs, these pilots seldom encounter high density altitudes or extremely cold temperatures. Furthermore, this reduced opportunity to rehearse these concepts may have been accompanied by a reduced emphasis on the same knowledge areas during training. These factors might explain the modest performance we observed on questions 5 and 9. Perhaps pilots from a geographical area in which high elevations and extreme temperatures are common might do better.

Experiment 2

The purpose of this experiment was to test our hypothesis about knowledge specialization: that pilots' knowledge may become fine-tuned to the charts and procedures associated with aircraft they fly, and that more general problem-solving knowledge they learned during initial training gradually fades.

To test this hypothesis, we recruited a sample of pilots who flew regularly in one make and model single-engine airplane and who had never flown in a second make and model single-engine airplane. These pilots were asked to solve weight and balance problems in both airplanes. It is important to note that all pilot participants held at least a private pilot certificate with an airplane category and single-engine class rating. This means that all pilots were certified to operate any (non-turbojet) single-engine airplane.

If our hypothesis about knowledge specialization is correct, pilots will be more successful at solving the weight and balance problems in the familiar airplane.

Apparatus

A paper and pencil test was used for data collection. Each test contained three weight and balance problems drawn from a test bank of four possible problems as follows. Two problems used weight and balance charts for a single-engine domestic airplane for which all pilots had significant experience and had flown within the preceding days. The remaining two problems used weight and balance charts for a different single engine domestic airplane that none of the pilots had ever flown. One problem for each manufacturer's charts resulted in a within-limits solution, while the other problem resulted in an out-of-limits or "no go" solution. Each problem required pilots to do three things: (1) calculate gross weight; (2) calculate total moments; and (3) determine whether the airplane was safe to fly as loaded. The test was accompanied by a questionnaire that asked participants about the certificates and ratings they hold and their total and recent flight time.

Participants

Twenty-four current and active pilots recruited from local California Bay Area airports participated in the study. Pilots received a NASA Aviation t-shirt as compensation for participating in the study.

Procedure

The experimental tests were completed by participants at times of their choosing. There was no time limit for completing the test. All participants were informed that their responses would remain anonymous.

Results and Discussion

The results for the four problems are shown in Table 5. Each problem was graded using three criteria: (1) correct weight calculation; (2) correct balance calculation; and (3) correct decision about whether the airplane was loaded within limits.

Table 5
Mean scores for weight and balance problems

Familiar Airplane						Unfamiliar Airplane					
Within Limits			Out-Of-Limits			Within Limits			Out-Of-Limits		
Wt.	Bal.	Go?	Wt.	Bal.	Go?	Wt.	Bal.	Go?	Wt.	Bal.	Go?
.83	.89	.78	1.0	.94	.83	.94	.83	.78	.94	.5	.5

There was a significant difference between the Unfamiliar Airplane Out-Of-Limits problem and all other problems. No other significant differences between the other problems were found.

Table 6 shows correlation coefficients comparing scores on the weight and balance problems and total and recent flight and teaching experience.

Table 6
Correlations between recent flight and teaching experience and scores on weight and balance problems.

Total Flight Time (n=18)	Last 6 Months n=18)	Total Dual Given (n=11)	Dual Last 6 Months (n=11)
-.21	.19	-.65	.28

A slight negative correlation was observed between total flight time and test scores. This effect was reversed in the presence of higher recent flight experience.

A significant negative correlation was observed between test scores and total dual instruction given among the flight instructor participants (df=9, t=2.26, $p < .05$). This effect was reversed in the presence of higher recent dual instruction given experience.

The results suggested two interesting conclusions. First, there is reasonable evidence to support the hypothesis that pilots well retain the particulars of the aircraft weight and balance charts they use everyday, and are less skilled at using charts for difference airplanes. Pilot who had never flown our control airplane were able to recognize a “no go” situation only 50 percent of the time. It can be argued that this result is natural: problem solving will be better for anyone using familiar materials. However, it must be remembered that holding a pilot certificate with a category and class rating means that the pilot is privileged to operate any aircraft of that category and class – without any further formal training or evaluation.

Second, there is little reason to believe that total flight time means higher proficiency in solving weight and balance problems. Furthermore, it seems that as flight instructors spend more time in the dual instruction role, the worse they become at solving weight and balance problems. This effect seems to be mitigated as the flight instructor's recent teaching experience increases.

Lastly, we must be careful in comparing the scores on weight and balance problems for this experiment, and the scores observed on the weight and balance problem in Experiment 1. The problem used in Experiment 1 was a multiple-choice FAA test question (1-in-3 chance of a successful guess), whereas the problems used in this experiment graded pilots across each step of their work.

Experiment 3

The purpose of this experiment was to test the hypothesis that pilots develop and use simplifications for aeronautical knowledge that requires tedious rote memorization. In the case of regulations, a simplification might discard difficult-to-remember details in favor of a simpler rule that, while not correct according to the regulations, allows pilots to operate legally.

To illustrate the notion of simplification, suppose a pilot states that, for all Class G airspace situations, the minimum visibility is 5 statute miles, while the minimum distance from clouds is 1,000 ft. above and below, and 1 statute mile horizontal. This simplification results in knowledge that is incorrect according to the regulations, yet allows him to operate legally in all Class G airspace situations. Now suppose a different pilot states that the minimums for all Class G airspace are 1 statute mile visibility and clear of clouds. This simplification results in knowledge that is both incorrect and not legal.

Our distinction between correct and legal answers affords us the opportunity to explore one more interesting twist: how certain pilots are about their answers. That is, if pilots are using simplifications, are they aware of them? Will pilots who provide "merely legal" answers recognize this situation, or will they confidently (and mistakenly) say that their answers are correct and "by the book?"

To answer these questions, we asked a group of pilots to answer six questions about regulations, and scored their answers as correct, legal, or altogether wrong. For each question, pilots were also asked to indicate (yes or no) if they were certain that their answer was correct according to the regulations, or if they were uncertain and would use their answer to operate legally.

If the hypothesis about knowledge simplification is correct, pilots will provide answers that are legal but not necessarily correct.

Apparatus

A paper and pencil, multiple-choice was used for data collection. Each test contained the same six questions, in shuffled order.

Three questions asked pilots to supply VFR weather minimums for Class G airspace in three different situations (14 CFR 91.155):

- Day, 1,200 ft. or less;
- Day, more than 1,200 ft. but less than 10,000 ft;
- Night 1,200 ft. or less.

The three remaining questions asked pilots about rules for operating at night:

- What time can a pilot begin logging night flight (14 CFR 1.1)?
- At what time must an airplane have operational position lights (14 CFR 91.209)?
- What time must passengers be dropped off if the pilot has not met the recent flight experience requirements for night flight (14 CFR 61.57(b))?

It is important to note that none of the questions were trick questions or an attempt to "split hairs" by offering answer choices that differed by one minute in order to test pilots' understanding of the minutiae of a rule. A basic understanding sufficed to answer all questions.

Participants

Eighteen current and active pilots recruited from local California Bay Area airports participated in the study. Pilots received a NASA Aviation t-shirt as compensation for participating in the study.

Procedure

The experimental tests were completed by participants at times of their choosing. There was no time limit for completing the test. All participants were informed that their responses would remain anonymous.

Results and Discussion

The results for the six questions are shown in Table 7.

Table 7

Scores and certainty measures for regulations questions.

Class G 1			**Class G 2**			**Class G 3**		
Correct	Legal	Wrong	Correct	Legal	Wrong	Correct	Legal	Wrong
.67	1.0	0	.5	1.0	0	.89	1.0	0
Certainty								
.72			.67			.78		
Correlation: Certainty / Correctness								
r=.35			**r=.47**			r=-.19		

Night 1			Night 2			Night 3		
Correct	Legal	Wrong	Correct	Legal	Wrong	Correct	Legal	Wrong
.61	.72	.28	.56	.89	.11	.44	.89	.11
Certainty								
.78			.83			.72		
Correlation: Certainty / Correctness								
r=.12			r=.06			r=.31		
Correlation: Legal / Correctness								
r=-.03			r=-.16			r=-.22		

The results directly supported the hypothesis about knowledge simplification: pilots characteristically gave incorrect yet legal responses.

Perhaps the most interesting results pertain to the certainty measures. Despite being given the option to say they were unsure, pilots frequently stated that they had provided the correct answer when in fact they had provided a merely legal answer, or an answer that was neither correct nor legal. On only one question did pilots' certainty significantly correlate with the correctness of their responses. This suggested that pilots had not only forgotten the regulations but were also unaware they had forgotten them. The certainty data also ruled out the theory that pilots offload the burden of remembering weather minimums and simply look them up prior to flight, or rely on notes during flight. If pilots followed such a strategy, it seems unlikely that their certainty estimates would be so high and so far amiss.

Experiment 4

This last experiment aimed to test our hypothesis that pilots in different geographical areas would exhibit greater retention of aeronautical knowledge that was more applicable to their own environment. To test this hypothesis, we selected eight questions about density altitude and airplane performance from the FAA Private Pilot knowledge test bank and administered them to pilots in two geographical areas: (1) the California coast during the winter; and (2) Denver, Colorado during the summer. Four questions were "conceptual questions" that probed pilots' understanding of the concepts that underlie density altitude. The remaining four questions asked pilots to use charts, perform calculations, and solve density altitude and airplane performance problems. The average elevation of the California airports at which pilots were recruited was 28 ft. The average elevation of the Colorado airports was 5770 ft. The average daily peak temperature in California during data collection was approximately 50 degrees Fahrenheit. The average daily peak temperature in Colorado during data collection was approximately 95 degrees Fahrenheit.

Apparatus

A paper and pencil, multiple-choice test was used for data collection. Each test contained the above-described eight density altitude questions. The test was accompanied by a questionnaire that asked participants about the certificates and rating they held and their total and recent flight time.

Participants

Thirty-six current and active pilots participated in the experiment. Eighteen pilots were recruited from local California Bay Area airports during winter. The remaining eighteen pilots were recruited at two airports located in Denver, Colorado during the summer. The mean and standard deviation for total number of flight hours for pilots in the California group and Colorado group were 1025 (978) and 936 (1238), respectively. Pilots received a NASA Aviation t-shirt as compensation for participating in the study.

Procedure

The experimental tests were completed by participants at times of their choosing. There was no time limit for completing the test. All participants were informed that their responses would remain anonymous.

Results and Discussion

The mean scores and standard deviations for the two groups are shown in Table 8.

Table 8
Mean scores for density altitude test for California and Colorado groups.

	Overall Score	Concept Questions	Problems
California Coast	.85 (.13)	.97 (.24)	.74 (.08)
Denver, Colorado	.86 (.14)	.97 (.23)	.75 (.08)

The scores for the two groups were nearly identical, offering no support for our hypothesis that pilots who operate everyday in high density altitude conditions know more than pilots who operate at sea level in a cool climate. This result is both surprising and counterintuitive. There are a number of possible explanations for this outcome, and for why the hypothesis may warrant further investigation.

First, most pilot participants in both groups were students and flight instructors who worked in a training environment at local flight schools. It may be that these two environments are more similar than we suspected. The airplanes used at each flight school were able to take off, climb, and land at any time of the day at either location. Furthermore, there is no significant terrain within close proximity of either airport to make climb rates an immediate safety issue. A future study that recruited workaday pilots who fly between small mountain airports might find that these pilots exercise their knowledge about density altitude and airplane performance to a larger extent, and therefore retain a greater mastery.

Second, our third experiment established that pilots devise and use simplifications of aeronautical knowledge they have learned. There are a number of "rules of thumb" that can be used in lieu of performing more tedious density altitude and takeoff performance calculations. For example, at an average field elevation of 5,770 feet, density altitude can be approximated by simply adding two zeros to the temperature in Fahrenheit. Depending on atmospheric pressure, density altitude is roughly 7,000 feet at 70 degrees, 8,000 feet at 80 degrees, 9,000 feet at 90 degrees, etc. Pilots may also rely on practical rules for takeoff performance such as the "70-50" rule: if the airplane has not developed 70% of the target rotation speed after using 50% of the available runway, the takeoff should be aborted.

Lastly, it may be that our decision to use FAA test questions to test what pilots know about density altitude and airplane performance was entirely insensitive to what knowledge pilots retained, and what new knowledge they have acquired. Perhaps a future study that undertook a more detailed review of pilot knowledge, beyond standardized multiple-choice questions, could reveal differences in what pilots know.

Summary and Conclusions

Four experiments were conducted to help understand how well everyday flying experience provides pilots with the opportunity to rehearse and retain aeronautical knowledge. In our first experiment, ten questions selected from the FAA private pilot knowledge test were given to a group of sixty pilots. The average score for all ten questions was 74.8%. Using information we gathered from the sixty pilots about their past and present aviation activities, we attempted to relate retention of the aeronautical knowledge tested by the ten questions to seven aspects of pilot experience. It was found that the certificates and ratings held by pilots have little influence on how well those pilots retain what they have learned during training. The current role played by the pilot (teacher, student, or neither) has a marginally significant effect: better retention is indicated for pilots who currently teach or learn in a flight training environment. Total flight experience seems to have little effect on knowledge retention while recent flight experience is associated with better retention, especially for flight instructors. Proximity in time to past flight reviews and upcoming practical tests was associated with better retention. Finally, better retention was found among applicants who reported frequently reading more aviation-related materials. Overall, the seven factors of pilot experience we considered accounted for portions of the variability in test scores, but left much unexplained.

An analysis of the ten individual test questions led us to make three additional hypotheses, not about pilots, but about the characteristics of the aeronautical knowledge itself, the charts that pilots use, and the geographical regions in which pilots use their knowledge. It was shown how aeronautical knowledge that requires rote memorization of facts and details is better remembered when mnemonics are used. Our second experiment showed how pilots had become accustomed to the weight and balance charts found in airplanes that are familiar to them, while their ability to solve the same weight and balance problems in other airplanes was less than what is expected of a private pilot applicant. The third experiment demonstrated how pilots appear to substitute simplified rules in place of more complex regulations that require memorization of detailed facts, and how pilots are often unaware that they have made this simplification. A fourth experiment examined the effect of geographical region on retention of aeronautical knowledge by testing pilots for superior retention of knowledge that pertained to their own local weather patterns. It was found that pilots who taught and trained in a high-density altitude environment performed no better or worse than pilots who taught and trained in a cool, coastal climate.

Overall, the results cast considerable doubt on the assumption that everyday flying or teaching experience, together with the current recent flight experience and flight review requirements, will naturally offer pilots the opportunity to practice and keep fresh the entirety of what they have learned. The results indicate a need for regular study, not only in areas of suspected disuse, such as regulations, emergencies, and unfamiliar weather patterns, but also in areas that seem more familiar. Indeed, the results disconfirm simple theories about what knowledge is used regularly and retained and what knowledge is not. The results for weight and balance problems using familiar aircraft charts demonstrate that pilots may not get as much practice in some areas as our intuitions may suggest. The certainty measures associated with incorrect responses to questions about regulations further demonstrate that pilots do not always know what they do not know.

The results indicated a need for more explicit standards for ongoing aeronautical knowledge proficiency. One possibility might be a system of self-certification similar to the recent flight experience requirements specified by U.S. 14 CFR 61.57. Pilots complete the requisite number of takeoffs, landings, or instrument procedures, and note these events in their pilot logbooks. Another, perhaps more controversial, alternative is to create a more detailed and frequent evaluation for aeronautical knowledge beyond the one-hour flight review required by U.S. 14 CFR 61.56.

Limitations of Our Study

There are a number of limitations of our study that warrant consideration.

What Do Pilots Really Need To Know?

A key assumption of our study was that pilots needed to know the aeronautical knowledge tested by the questions drawn from the FAA private pilot knowledge test bank. It might be argued that, even though the knowledge is required for the FAA knowledge test, the material covered by these questions did not adequately represent what a pilot operating in the national airspace system really needs to know. This argument seems potentially valid for some of our original ten test questions. For example, our own hypothesis could be used to argue that what is important is that pilots be able to solve weight and balance problems in their own airplanes. Pilots' ability to solve these problems using the different charts found in FAA questions may not matter much. However, this argument is rejected by the modest scores achieved by pilots in our second experiment in which familiar weight and balance charts were used. Making a correct go/no-go decision four out of five times in a familiar aircraft is simply not sufficient. Another argument could be made about the question in which pilots were asked to interpret a VOR indication without being able to center the needle. A convincing argument would need to prove that no pilot could ever look at a VOR indication configured as such and draw an erroneous conclusion that subsequently went uncorrected.

What Do Other Kinds of Pilots Remember?

Another limitation of our study is that we only considered pilots drawn from a small portion of the general aviation population: pilots who teach, learn, and fly at flight training/aircraft rental establishments in metropolitan areas. We have already recognized the possibility that pilots who fly in other areas, under less routine circumstances in different geographical areas, may exhibit different knowledge retention than what we have observed. Perhaps airline, medical evacuation, and crop-duster pilots all exhibit different patterns of remembering and forgetting.

The Role of How Aeronautical Knowledge Is Initially Learned

It is widely known that memory for any type of learned material is affected by how that material is initially studied and learned. Memory for material memorized and rehearsed in a rote manner is weaker than for material that is processed in more elaborate and meaningful ways (Craik & Lockhart, 1972; Frase, 1975; Stein & Bransford, 1979). There is already considerable evidence that pilot applicants sometimes engage in crude memorization exercises to expedite passing of FAA pilot knowledge tests, at the expense of true understanding of the material (Casner, Jones, Puentes, & Irani, 2003). This suggests the possibility of a more dire interpretation of the test scores we observed. It may be that some pilots never truly understood the material probed by our questions, and therefore had difficulty recalling it as a collection of rote-memorized facts.

This hypothesis raised the question of how best to teach aeronautical knowledge. A common criticism of current aviation teaching methods is that many areas of aeronautical knowledge are taught in the abstract, that is to say, outside of the context in which they are to be used. Throughout the history of education, there have been repeated attempts to implement the practice of teaching knowledge and skills in specific and practical contexts (Dewey, 1938; Lave, 1988). In each case, a perhaps overzealous attempt to implement context-specific learning has arguably led to a later deterioration in fundamental skills. In each case, the teaching-in-context movement was later overthrown by a more conservative "back-to-basics" movement (Ravitch & Finn, 1989; Bloom, 1988). As Carroll (1990) pointed out, education is "frequently subject to headline whims and demagoguery (p. 1)" and "is chronically subject to trends (p. 1)." It is not clear whether or not recent attempts to reincarnate this idea, under the name of 'scenario-based training,' will avoid these same pitfalls.

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